Performance of the Real-Time Array Signal Combiner During the Voyager Mission

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The technique of station arraying is used to improve the signal-to-noise ratio by reinforcing the coherent spacecraft signal while cancelling out location-dependent incoherent noise. The signal combiner provides a delay compensation that keeps the signals correctly phased throughout the spacecraft pass. The signals are combined to optimize the signal-to-noise ratio of the sum. The combined signal is then processed in the normal manner by the rest of the telemetry chain.

During the Voyager Mission each Deep Space Station used its 64-meter antenna together with a 34-meter antenna to form an array. Data were selected from the Saturn encounter period from November 2 to November 13, 1980, to analyze the signal combiner performance. A statistical analysis of the residual gain data from all of the arrayed Deep Space Stations indicates that the Real-Time Combiner is operating within the designed accuracy range of 0.2 ±0.05 dB around the theoretical gain. A decrease in the residual gain value appears to correlate with an increase in antenna elevation, which may be directly related to the changing antenna gain with elevation. Overall, the combined signal-to-noise ratio is improved by an average of 0.62 ±0.15 dB over the 64-meter signal-to-noise ratio alone.

I. Introduction

A spacecraft signal can be degraded in one of two ways. There can be loss of desired signal relative to noise, where a portion of the signal is diverted, scattered or reflected from its intended route, or there can be an increase of noise relative to the desired signal. Noise can originate as unwanted signal energy injected into the link, or as thermal noise generated within the link. There is a consistent level of degradation of the spacecraft signal from space loss, due to a decrease in the electric field as a function of distance and due to noise injection from the 3°K temperature of space, which is independent of the location of the receiving station. However, there are sources of loss and noise which are highly location-dependent. Some of these are atmospheric loss due to water vapor and oxygen, scintillation fades due to atmospheric multipath phenomena, terrestrial noise, line loss between antenna and receiver, and thermal noise generated within the receiver. Of all the sources described, the spacecraft signal is particularly susceptible to degradation from the last two since the signal is at its lowest energy level at these stages.

The fact that a spacecraft signal received simultaneously at several Deep Space Stations is affected by an independent noise contribution at each station is the significant factor that

makes the technique of station arraying possible. An improvement in signal-to-noise ratio (SNR) is achieved by combining the outputs from various receiving locations in an appropriate manner to reinforce the coherent spacecraft signal while cancelling out incoherent noise from the stations. This involves compensating for phase delays at each station caused by differing spacecraft-to-station distances and by differing signal relay times to a common site.

II. Functional Description of the Signal Combiner

A simplified block diagram of the baseband signal combiner is illustrated in Fig. 1. The signal combiner provides a delay compensation that automatically tracks the changing signal delays to keep the signals correctly phased throughout the spacecraft pass. This variable delay compensates for the change in signal arrival time at the different antennas as the Earth rotates during the mission viewing period.

Once properly phased, the signals are combined in a weighted average depending upon their relative average SNRs. The weighting gain factors are chosen to optimize the SNR of the sum in a manner discussed in detail by R. A. Winkelstein (see Bibliography). The combined signal proceeds from the output of the Real-Time Combiner to the baseband input of the Subcarrier Demodulator Assembly (SDA). From there on, the signal is processed in the normal manner by the rest of the telemetry chain.

III. Operational Detail of the Signal Combiner

The heart of the signal combiner is the phase tracking channel. This is illustrated in Fig. 2. Its function is to provide a continuously variable amount of time delay to match the signals at the summing amplifier to the reference baseband signal. The values of the delays are determined by a central processing unit (CPU) controlled tracking loop.

The combiner input signals pass through essentially identical input amplifiers and are converted from analog to digital. For the reference channel the sign bit is switched onto a bus to be used by the correlator sections of the other channels. The baseband signals from each station are sampled by a multiplexed digital FIFO memory at approximately a 10-MHz rate.

The FIFO memory system consists mainly of the multiplexed FIFO and a fill counter. The memory holds digital samples which are input to the memory using the input strobe and output from the memory using the output strobe. The buffer output rate is determined by a fixed common clock

line. The buffer input rate is governed by a separate variable clock, but the input strobes are independent of each other and are generated asynchronously with respect to the output clock.

The resident time of a particular sample in memory is the delay time. The length of time a sample remains in the buffer is a function of the number of samples in memory, as indicated by the fill counter, and the phase difference between the input and output strobes. Therefore, the time delay can be continuously adjusted by controlling the input clock frequency.

At the output of the FIFO, the delayed signals are correlated with the reference signal. When the signals agree in phase, the correlation is at its maximum. For each channel, the correlation of the reference signal with the input signal advanced by 90 degrees of phase and the correlation of the reference signal with the input signal retarded by 90 degrees of phase are developed. The difference of these two correlation curves, designated quadrature correlation, crosses zero when the input signal is aligned with the reference signal (see Fig. 3). Therefore, quadrature correlation is suitable as a control function for the delay on each channel of the tracking loop.

Each second the quadrature correlator produces a digital count, which is a function of the relative signal delay. The quadrature correlator count represents an integral of the input signal phase difference averaged over a time period of one second. The quadrature correlator should produce a count of zero when the input signals are exactly aligned. When they are not aligned, the count is proportional to the phase timing error between the signals.

The digital count is scaled by the CPU and converted to analog voltages by digital-to-analog converters. These voltages are applied to the input of the voltage-controlled oscillators (VCO's). The output frequency of the VCO produces a slight change in the FIFO input strobe rate, thus closing the control loop. As a result, the signal delay is changed in the direction to force the error count out of the quadrature correlator to zero.

At the output of the FIFO buffer, with the signals aligned in phase, the signals are reconverted to analog by a digital-to-analog converter. They are then weighted by gains calculated to optimize the SNR of the combined signal and applied to the input of the summing amplifier. Once combined, the signal flows through the telemetry processing chain in a normal manner.

IV. Voyager Mission Performance

During the Voyager Mission, each Deep Space Station used its 64-meter antenna together with a 34-meter antenna to form an array. The input signal from each 64-meter antenna became the reference baseband signal in the phase tracking channel of its respective combiner.

To analyze array performance, data were selected from the Saturn encounter period from November 2 to November 13, 1980. The design of the Real-Time Combiner specifies a signal degradation of no more than 0.2 ±0.05 dB from the theoretical combined gain. The actual gain data contains this system-induced degradation plus external coherent noise injection which is not cancelled out by the combining process, such as from space and atmospheric phenomena.

The 64- and 34-meter uncombined SNR averages are recorded for comparison with the combined array SNR averages. At optimal performance the combined SNR is maximized to a theoretical value of

$$SNR_s = SNR_{64} + SNR_{34}$$

$$= SNR_{64} \left(1 + \frac{SNR_{34}}{SNR_{64}}\right)$$

where

$$A_{th} = \left(1 + \frac{SNR_{34}}{SNR_{64}}\right)$$

is the theoretical gain over the uncombined 64-meter signal. The actual gain is calculated from the data:

$$A_c = SNR_s - SNR_{64} \text{ (SNRs in dB)}$$

and the residual difference is calculated:

$$Residual = A_{th} - A_c \text{ (gains in dB)}$$

It is these residual values that demonstrate the performance capabilities of the Real-Time Combiner.

The data from the Deep Space Stations are plotted as a function of antenna elevation in Figs. 4, 6 and 8. A decrease in the residual gain value appears to correlate with an increase in the antenna elevation. This is particularly evident during adverse weather conditions which degrade the input signal markedly. Under these circumstances the improvement to the residual gain is pronounced as the antenna dish tracks to higher elevations. The change in residual gain as a function of elevation may be primarily affected by the change in antenna gain as a function of elevation. The antenna gain vs elevation curves are included for the 64-meter antennas as Figs. 5, 7 and 9 for comparison.

Figure 10 illustrates the distribution of the residual gain data from all of the arrayed Deep Space Stations. The statistical mean of 0.22 dB falls within the theoretical accuracy range of 0.2 ±0.05 dB predicted for the Real-Time Combiner.

The residual gains are also averaged on a pass-by-pass basis. These data are plotted in Figs. 11 and 12. Figure 13 shows the distribution of the pass averages from the arrayed Deep Space Stations. The statistical mean of 0.205 dB again falls within the theoretical accuracy range as predicted.

V. Conclusion

The Real-Time Combiner has performed well during the Voyager Mission, as the data samples taken during the Saturn encounter indicate. The actual improvement in the signal-to-noise ratio of the combined signal is an average of 0.62 ±0.15 dB over the 64-meter signals alone. The Voyager Mission data have demonstrated that antenna arraying operates as designed, providing a clear improvement in telemetry performance.

On November 7, 1980, the Australian complex, under heavy cloud cover and falling snow, received the Saturn pictures depicted in Fig. 14. The clarity of the arrayed pictures compared to the unarrayed pictures is striking, particularly in the face of such adverse weather conditions. These pictures illustrate the performance extension achieved with array technology.

Bibliography

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2. Wilck, H., "A Signal Combiner for Antenna Arraying," in *The Deep Space Network Progress Report 42-25*, pp. 111-117, Jet Propulsion Laboratory, Pasadena, Calif., Feb. 15, 1975.

3. Winkelstein, R. A., "Analysis of the Signal Combiner for Multiple Antenna Arraying," in *The Deep Space Network Progress Report 42-26*, pp. 102-118, Jet Propulsion Laboratory, Pasadena, Calif., April 15, 1975.
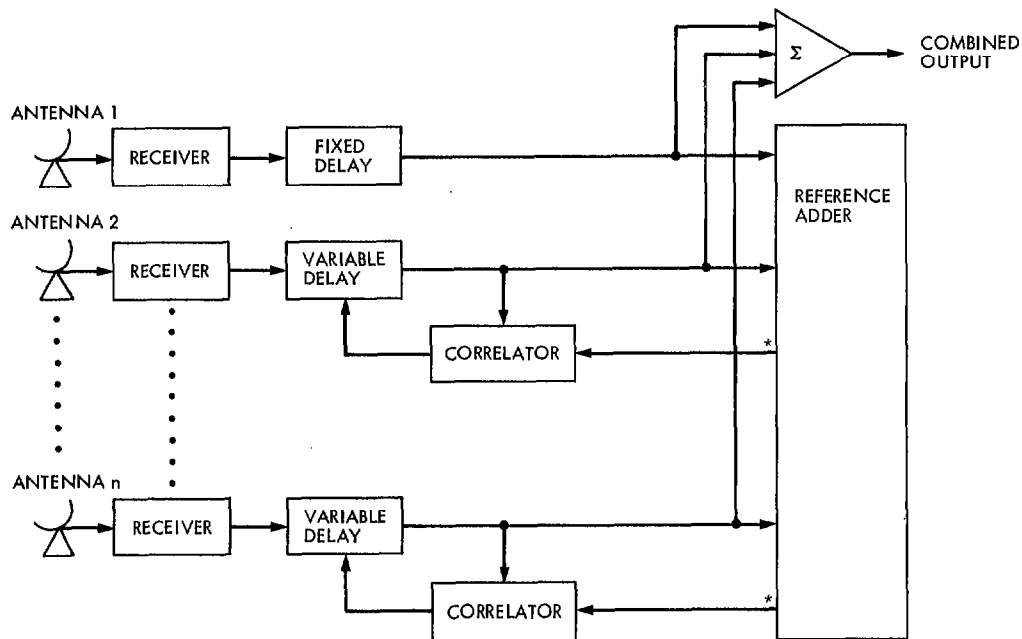
*. SUM OF SIGNALS FROM ALL OTHER ANTENNAS

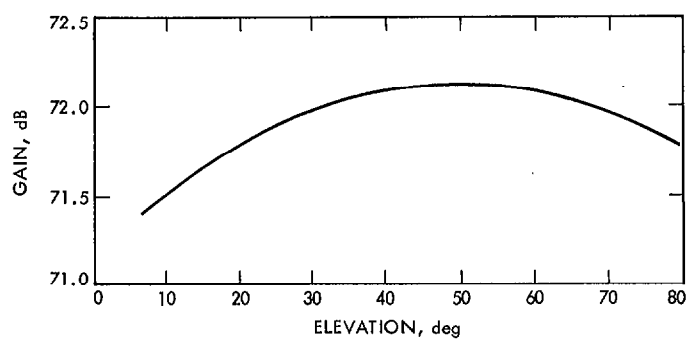**Fig. 1. Baseband signal combiner simplified block diagram**
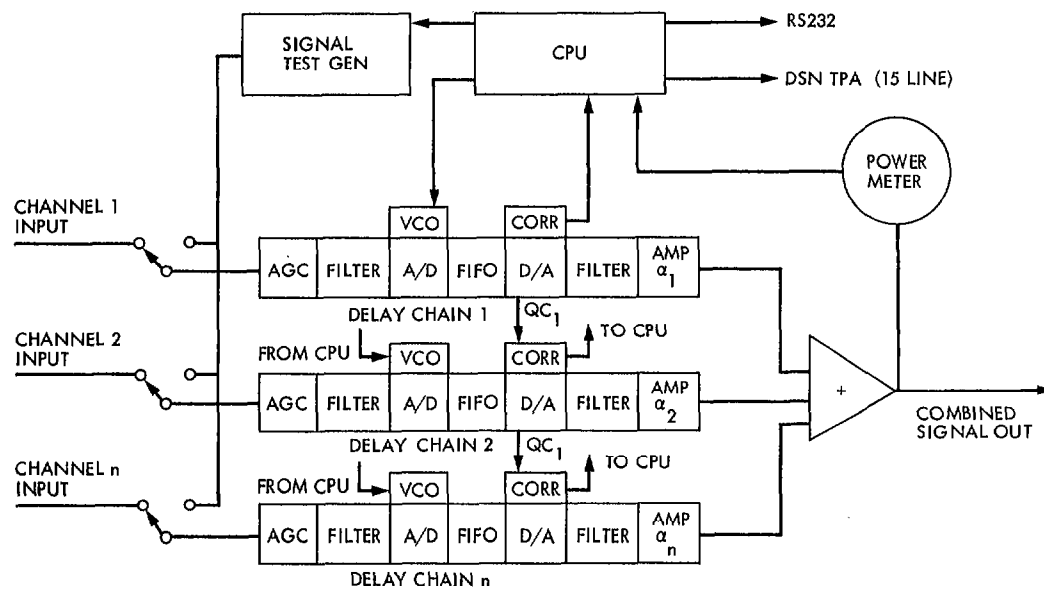
Fig. 2. RTA signal combiner block diagram

(a) SUBCARRIER IN PHASE WITH REFERENCE

(b) SUBCARRIER ADVANCED BY 90 deg

(c) SUBCARRIER RETARDED BY 90 deg

(d) QUADRATURE CORRELATION CURVE {(c) - (b)}
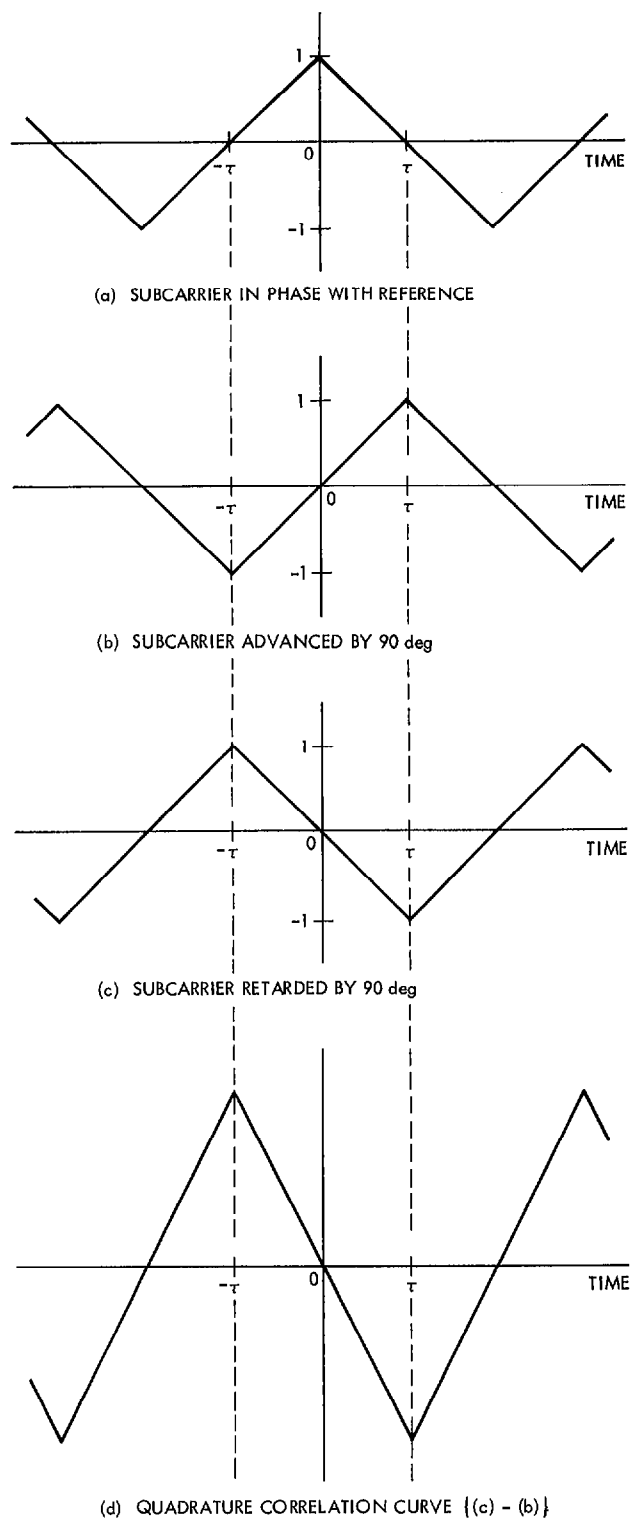
Fig. 3. Normalized correlation curves
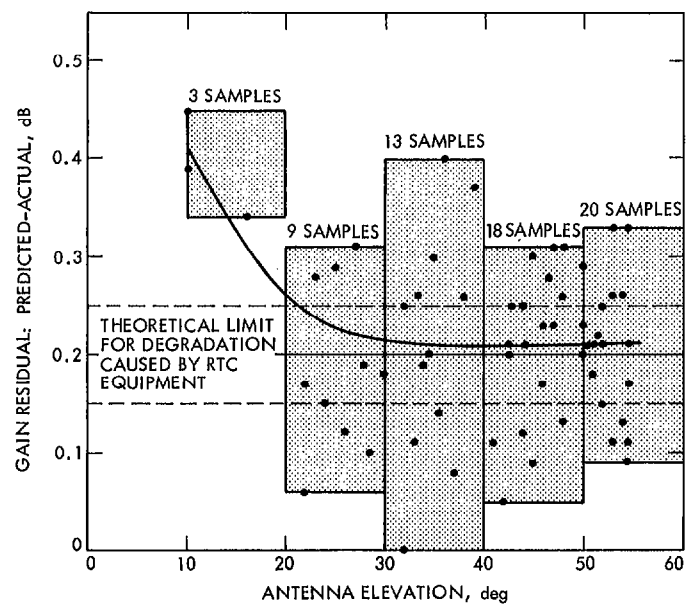
Fig. 4. Real-time combiner (44.8) hourly values,
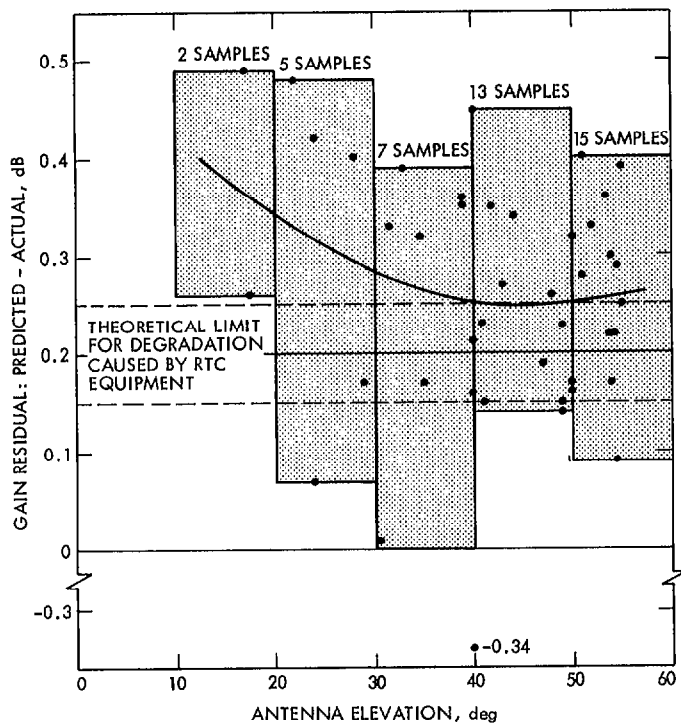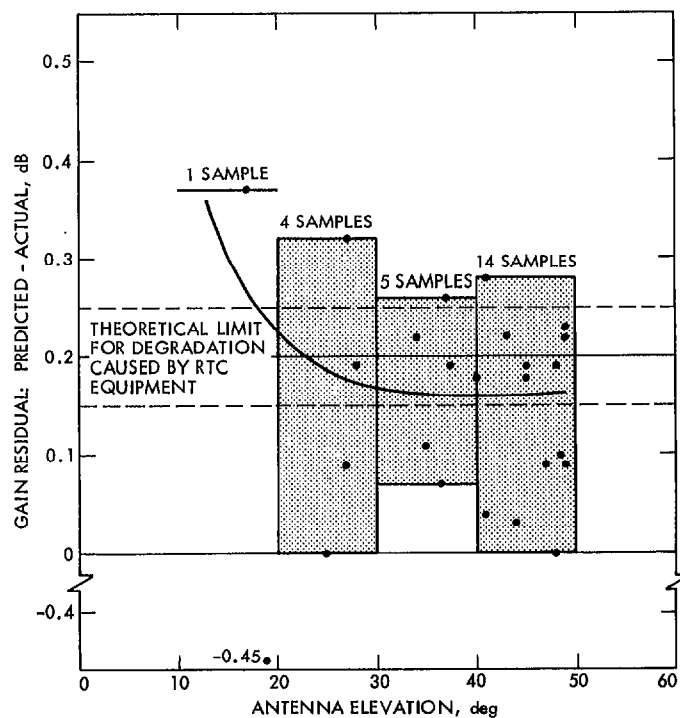DSS 12/14 array, DOY 306−317

Fig. 5. Gain vs elevation, X-band, DSS 14

Fig. 6. Real-time combiner (44.8) hourly values,
DSS 42/43 array, DOY 306–317

Fig. 8. Real-time combiner (44.8) hourly values,
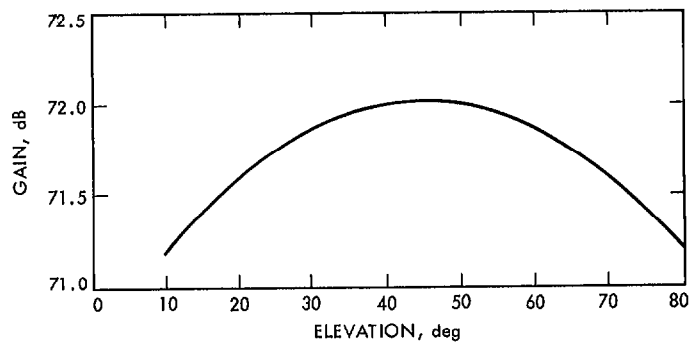DSS 61/63 array, DOY 306–317

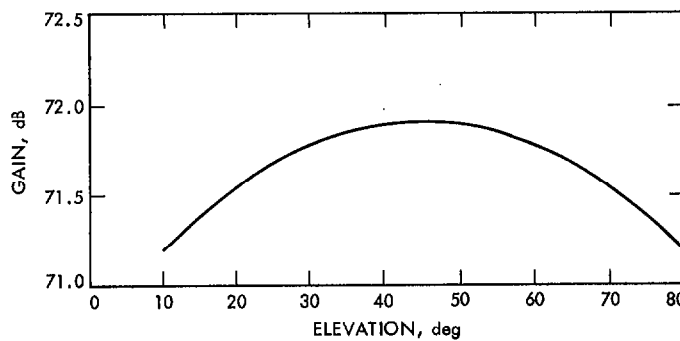Fig. 7. Gain vs elevation, X-band, DSS 43
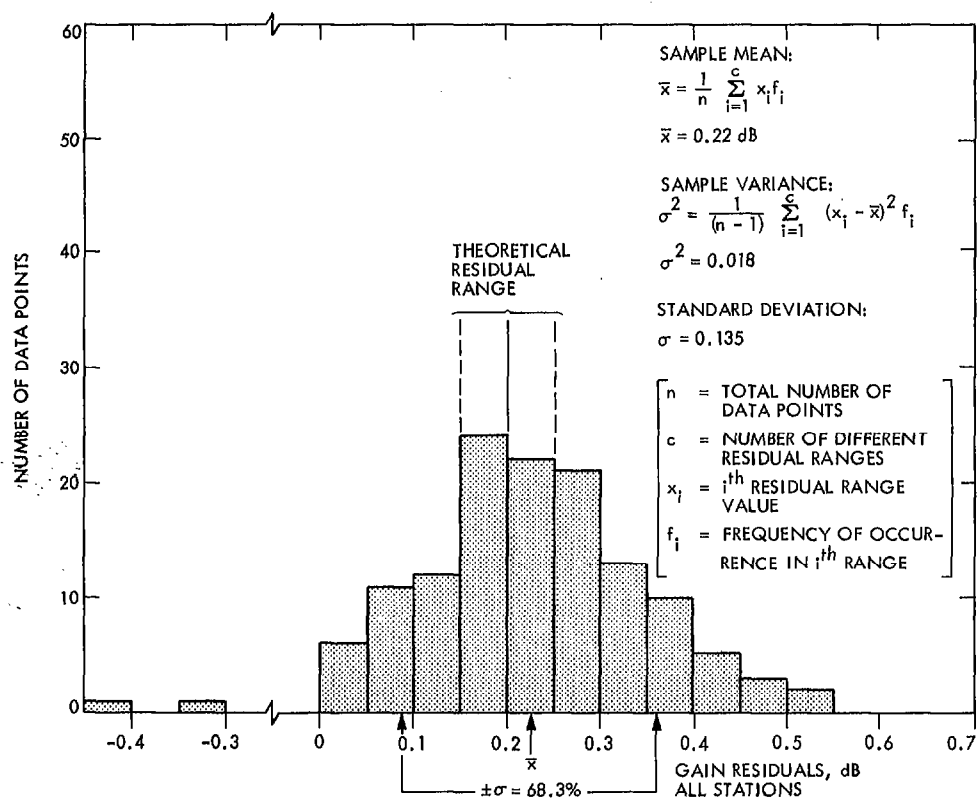

Fig. 9. Gain vs elevation, X-band, DSS 63
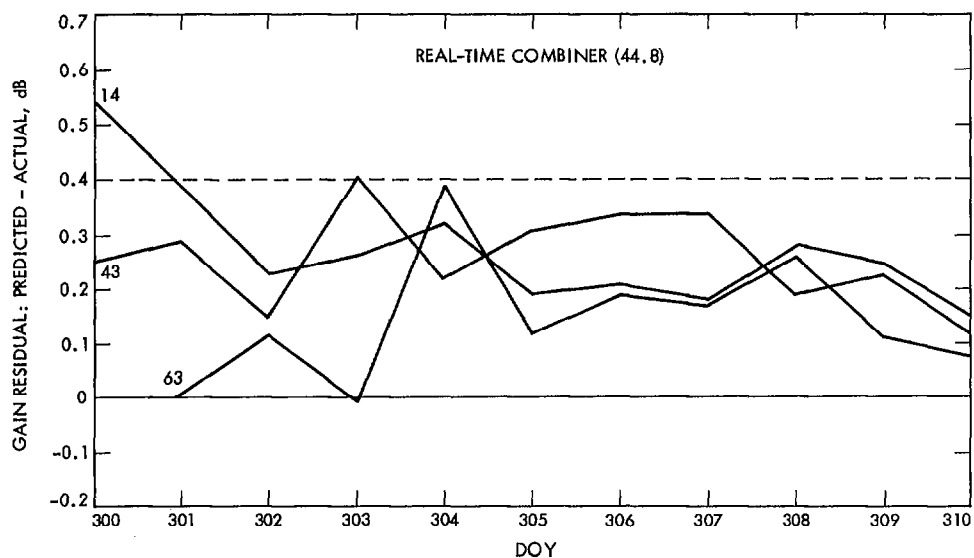
Fig. 10. Array data distribution
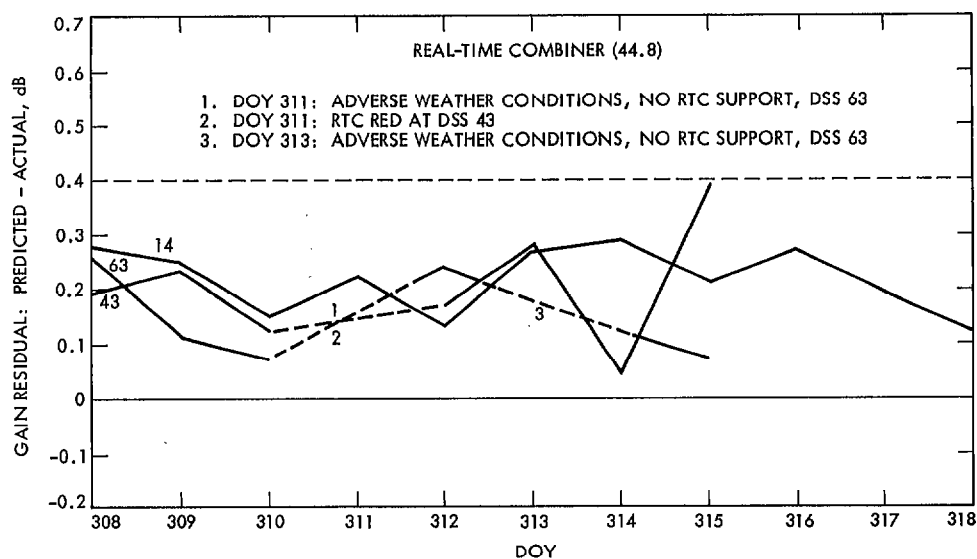

Fig. 11. Residual gain pass averages, DOY 300–310

Fig. 12. Residual gain pass averages, DOY 308–318

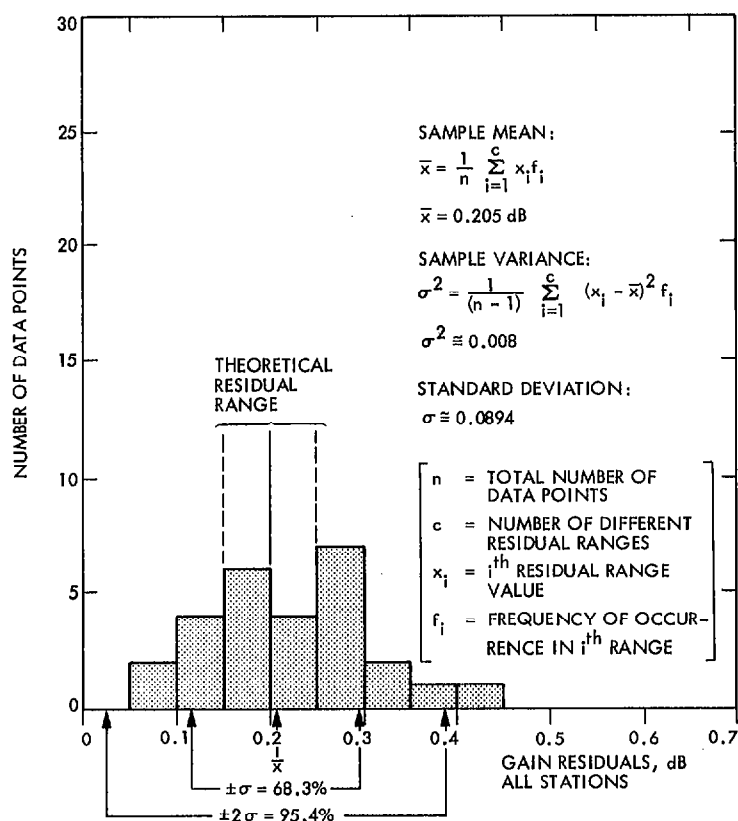**Fig. 13. Pass average data distribution**
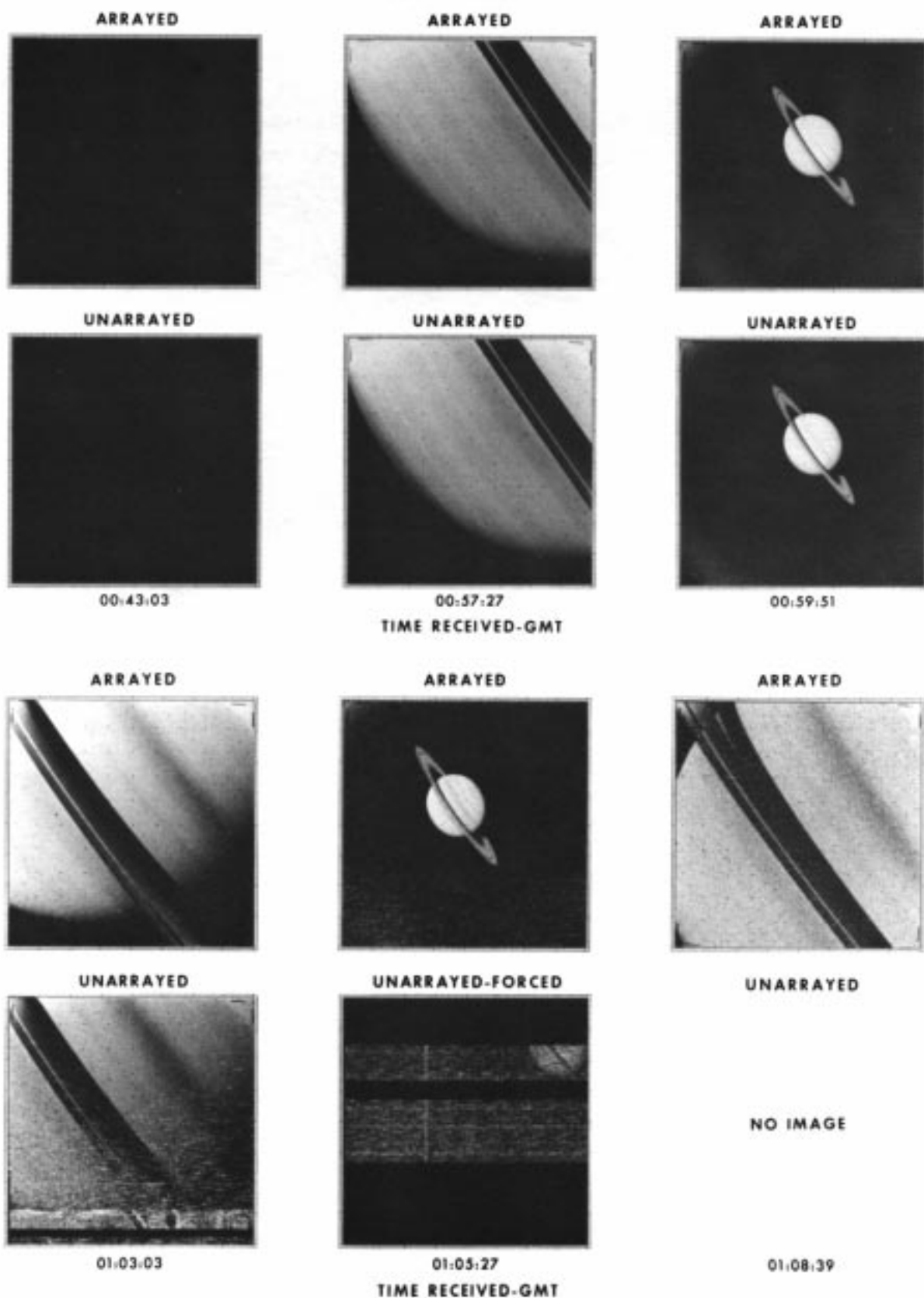
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UNARRAYED   UNARRAYED   UNARRAYED

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TIME RECEIVED-GMT

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UNARRAYED   UNARRAYED-FORCED   UNARRAYED

NO IMAGE

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TIME RECEIVED-GMT

Fig. 14. Array performance—Voyager 1 Saturn encounter (Australian Complex, November 7, 1980)

ARRAYED

ARRAYED

ARRAYED

UNARRAYED-FORCED

UNARRAYED

UNARRAYED-FORCED

NO IMAGE

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01:14:15

01:16:39

TIME RECEIVED-GMT

ARRAYED

ARRAYED

ARRAYED-FALSE F/L

UNARRAYED

UNARRAYED-FORCED

UNARRAYED-FORCED

NO IMAGE

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01:22:15

01:25:27

TIME RECEIVED-GMT

Fig. 14 (contd)

201

ARRAYED

ARRAYED

ARRAYED

UNARRAYED-FORCED

UNARRAYED-FORCED

UNARRAYED

01:27:51

01:31:03

01:33:27

TIME RECEIVED-GMT

ARRAYED

ARRAYED

ARRAYED

UNARRAYED

UNARRAYED

UNARRAYED

01:36:39

01:39:03

01:47:51

TIME RECEIVED-GMT

Fig. 14 (contd)